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# Light Stops at CDF?

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## Abstract

We study the possibility that the production and decay of light stop squarks at Tevatron can mimic top events. We show that this scenario is very unlikely to explain the anomalously high top production cross sections recently reported by the CDF collaboration.

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## 1 Introduction

Recently the CDF collaboration reported the first direct evidence for the existence of the top quark  $t$  [1]. Although the top mass range  $m_t = 174 \pm 10^{+13}_{-12}$  GeV inferred from the reconstruction of 10 events is compatible with precision electro-weak measurements,  $m_t = 178 \pm 11^{+18}_{-19}$  GeV [2], a number of questions remain unanswered. Perhaps the most pressing issue is the discrepancy between the measured cross-section and its theoretical expectation based on the mass range quoted above: the standard model predicts cross-sections significantly smaller than the one observed by CDF.

This discrepancy has prompted several authors to invoke the existence of a light stop squark  $\tilde{t}$  [3]. Indeed, theoretical expectations lead to a low mass for one of the two the supersymmetric partners of the top quark, if the latter is heavy [4]. Since a light stop has decay modes very similar to those of the top quark, this could lead to stop decays misidentified as top events. It is the purpose of this letter to demonstrate that, although light stops might well be produced at the Tevatron, they are very unlikely to explain the anomalously high event rates observed by CDF.

We first discuss the production and decay of stops in  $p\bar{p}$  collisions, establishing under which circumstances the signal does in fact resemble that of a top quark. Next we investigate the effects of the cuts CDF imposed to isolate its top signal from the overwhelming backgrounds. This allows us to make a comparison with the CDF results for a range of values of the top and stop mass, as well as other relevant supersymmetry parameters.

## 2 Total rates

In the following we assume the validity of the minimal supersymmetric standard model. Hence the lightest supersymmetric particle is a neutralino  $\tilde{\chi}_1^0$  which is stable because of  $R$ -parity conservation and typically escapes detection. For a heavy top quark it is realistic to assume the following hierarchy in the supersymmetric sector:

$$m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_{\text{all others}} . \quad (1)$$

In this case the stop can only decay via a virtual chargino or a (not necessarily virtual) top quark into

$$\tilde{t} \rightarrow \tilde{\chi}_1^0 W b . \quad (2)$$

This is exactly the same decay signature as the top  $t \rightarrow Wb$ , except for the extra missing energy carried away by the invisible neutralino. If condition (1) were to be relaxed and one or more sleptons are lighter than the stop, there are other decay mechanisms which compete with (2). The numerical difference with the results to follow is however not major and the overall conclusions of this study are not affected.

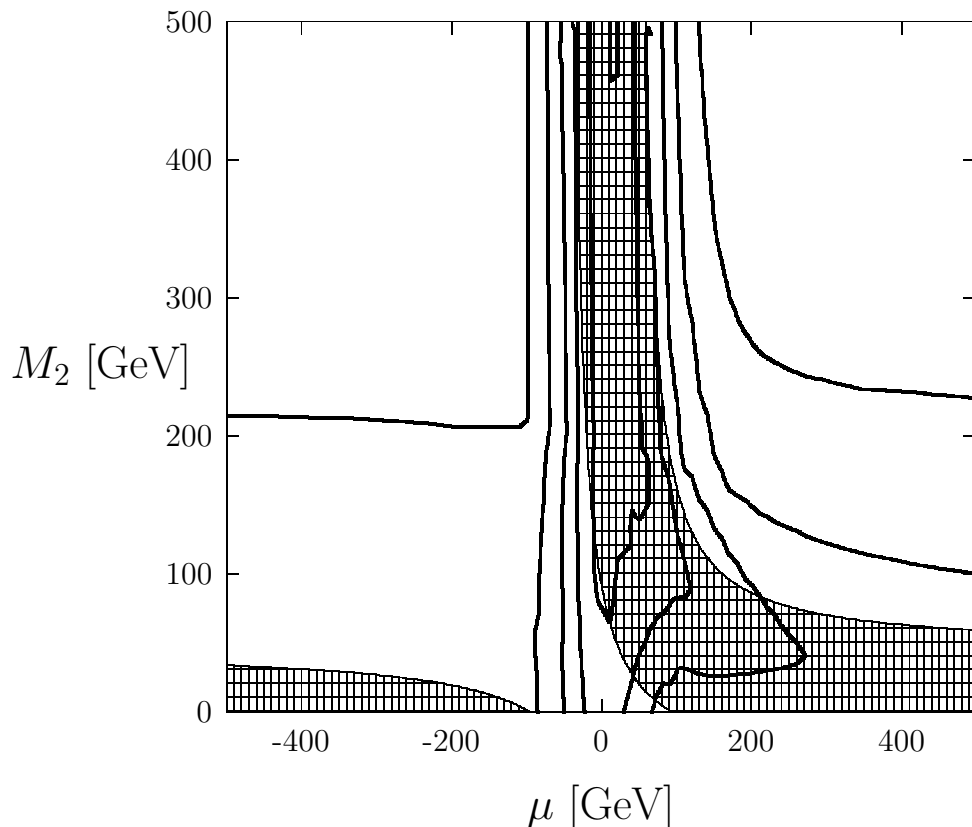


Fig. 1. Contours of the branching ratio  $BR(t \rightarrow bW) = .5, .6, .7, .8, .9, 1$ , from the innermost to the outermost curves. This set of contours has been obtained for  $m_t = 160$  GeV,  $m_{\tilde{t}} = 50$  GeV and  $\tan \beta = 1$ . For larger values of  $\tan \beta$  the plot becomes increasingly more symmetric with respect to the axis  $\mu = 0$ . The hatched area is excluded by LEP.

Stop quarks can be obtained from the production and decay of top quarks. The rates depend on the branching fractions of the decays  $t \rightarrow \tilde{t} + \tilde{\chi}_i^0$  ( $i = 1 \dots 4$ ), which in turn depends on various supersymmetry parameters. In practice, however, for most of the parameter space not yet excluded by the LEP experiments this branching ratio does not exceed more than 10–25%. This can be seen from Fig. 1, where we plotted several contours of equal  $t \rightarrow Wb$  branching fractions in the plane of the Higgs mixing mass  $\mu$  and the supersymmetry breaking mass  $M_2$  [5]. These contours have been plotted for the heaviest top mass expected at the  $1\sigma$  level from the rates observed at CDF ( $m_t = 160$  GeV, *cf.* next section), and for the lightest stop mass barely compatible with

other experiments. The branching ratio is thus likely to be closer to one than shown. The small branching combined with the paucity of top events mean that this channel can be neglected for stop production as compared to direct stop production. This also implies that the standard model prediction for top production remains largely unaffected by the existence of a lighter stop. In the following we will neglect altogether any possible deviation from one of the branching ratio  $t \rightarrow Wb$ .

Stops can also be directly pair-produced in hadronic collisions. The dominant mechanism at  $\sqrt{s} = 1.8$  TeV is  $q\bar{q} \rightarrow t\bar{t}$ , with  $gg \rightarrow t\bar{t}$  giving a small additional contribution [6]. The lowest order cross sections at Tevatron are shown in Fig. 2 along with the corresponding cross section for  $t\bar{t}$  production. The rates are not sensitive to the structure functions used as these are probed at large  $x$ . We have used the GRV LO set [7]. Higher order corrections have been computed for top production [8] and are also shown in Fig. 2. The large uncertainty is due to the choice of scale. In the absence of a similar  $\mathcal{O}(\alpha_s^3)$  calculation for the squark sector, we have assumed the same K-factors to hold for stop production. It appears that the supersymmetric channel could make a sizable contribution if the mass of the stop is about 50 GeV less than that of the top.

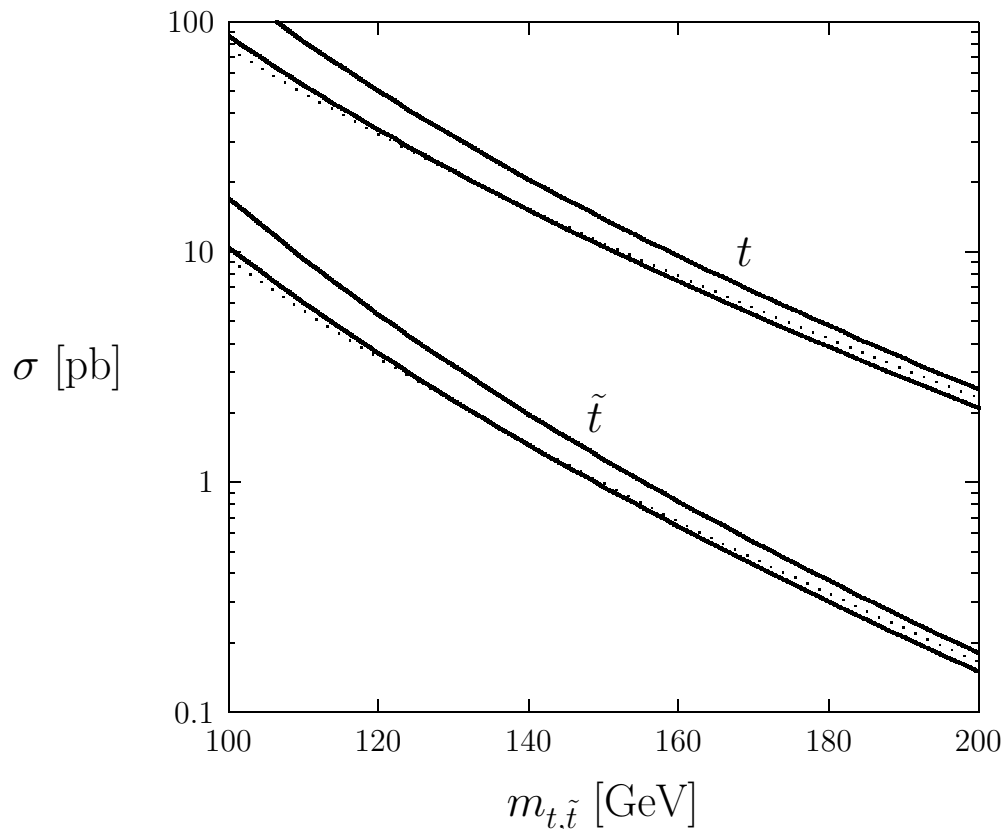


Fig. 2. Top and stop production at  $\sqrt{s} = 1.8$  TeV. The thick lines are the next to leading order results of Ref. [8]. The dotted lines are the lowest order result.

### 3 Observable rates

The CDF group concentrates on two types of top signals, according to two of the three possible decay modes of the  $W$  bosons which emerge from the decay of the top:

- dilepton:  $t\bar{t} \rightarrow \ell^+ \nu_\ell \ell'^- \bar{\nu}_{\ell'} b\bar{b}$ ;
- lepton+jets:  $t\bar{t} \rightarrow \ell^\pm \bar{\nu}_\ell^{(-)} q\bar{q}' b\bar{b}$ .

The cuts required by CDF to isolate the signal are described in detail in Refs [1]. To obtain an estimate of the influence of these cuts on the observability of the stop signal, we have performed a rough simulation of top and stop production and decay, assuming isotropic boosted decays and neglecting all fragmentation, hadronization and detector effects (*i.e.*, jets were represented by a single parton). Using the simulation we obtain efficiencies which are higher than the ones quoted by CDF by a factor 1.2 (lepton+jets) to 2 (dilepton) for  $m_t = 160$  GeV. The difference is due to the isolation and jet cuts, which cannot be implemented well at the parton level. The effect of these cuts, and hence the difference between our simulation and the CDF results, increases for lower masses.

The expected number of events  $n$  is computed as

$$n(m_t, m_{\tilde{t}}) = \mathcal{L} \sum_{\substack{\text{dileptons} \\ \text{lepton+jets}}} \sigma_t(m_t) \varepsilon_t^{\text{CDF}}(m_t) + \sigma_{\tilde{t}}(m_{\tilde{t}}) \left( \frac{\varepsilon_{\tilde{t}}(m_{\tilde{t}})}{\varepsilon_t(m_{\tilde{t}})} \right) \varepsilon_t^{\text{CDF}}(m_{\tilde{t}}), \quad (3)$$

where  $\mathcal{L} = 19.3$  pb is the integrated luminosity analyzed by CDF. The ratio of efficiencies  $\varepsilon_{\tilde{t}}/\varepsilon_t$  has been computed using our parton level Monte Carlo simulation, and should be fairly insensitive to the isolation and jet cuts. For masses exceeding 100 GeV the efficiencies  $\varepsilon_t^{\text{CDF}}$  are taken from Refs [1]. For lower masses no efficiencies are quoted and we have used our computed efficiencies corrected by the extrapolation of the factors mentioned above.

We have plotted in Figs 3 the efficiencies for the top and stop signals, the latter for three different neutralino masses. The sharp drops at the  $m_t = m_W + m_b$  and  $m_{\tilde{t}} = m_{\tilde{\chi}_1^0} + m_W + m_b$  thresholds are due to a cut of 85 GeV imposed by CDF on the scalar sum of observed transverse momenta (both in the dilepton and lepton+jets channels). Indeed, as the structure functions are quite steep most (s)top pairs are produced close to threshold. The decay  $W$  bosons and  $b$  quarks are then produced at rest in the (s)top rest frame, which is hardly boosted, and the decay products of the  $W$  are unable to pass the stringent transverse momentum cut.

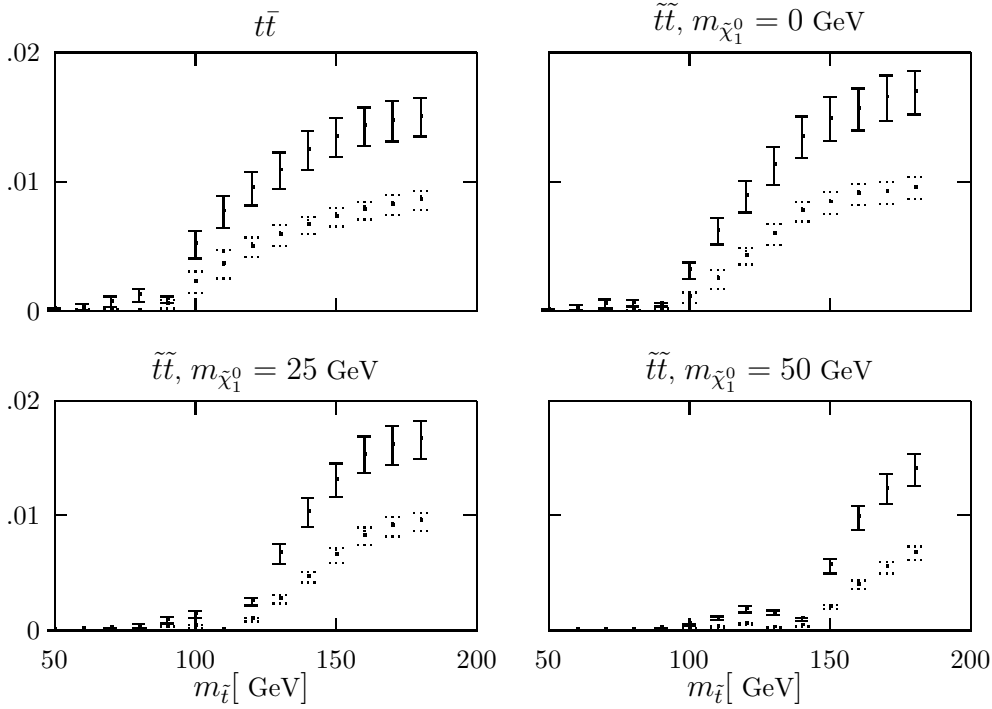


Fig. 3. Estimated efficiencies times branching ratios for the detection of top and stop pairs using the CDF top quark cuts. The upper solid points are for the dilepton channel, the lower dotted ones the dilepton channel

#### 4 Comparison with the CDF results

Equating the predicted number of dilepton and lepton+jet events Eq. (3) to the observed number of top candidate events (12) minus the expected background (5) modulo its Poisson fluctuation ( $7 \pm \sqrt{7}$ ), we can establish contours of one standard deviation in the  $(m_t, m_{\tilde{t}})$  plane. These are shown in Fig. 4 for three different values of the neutralino mass, where the areas to the right of the curves are forbidden at this confidence level. The theoretical uncertainty is added linearly, *i.e.*, it is taken into account by using in Eq. (3) the upper bound of the cross sections displayed in Fig. 2. If the stop squark is heavy or absent the rates observed by CDF are incompatible with a top mass in excess of 162 GeV at the  $1\sigma$  level, in contradiction with the mass inferred by CDF from the reconstruction of the 10 lepton+jet events,  $174 \pm 10^{+13}_{-12}$  GeV combined with the electro-weak measurement  $m_t = 178 \pm 11^{+18}_{-19}$  GeV. Combining these estimates of the top quark masses and the CDF cross section gives a minimum  $\chi^2 = 1.6$  at  $m_t = 164$  GeV. The  $1\sigma$  range is indicated by the arrow on Fig. 4.

It appears from Fig. 4 that a light stop squark is not likely to solve this puzzle. Only in the most optimistic scenario, when the neutralino is lighter

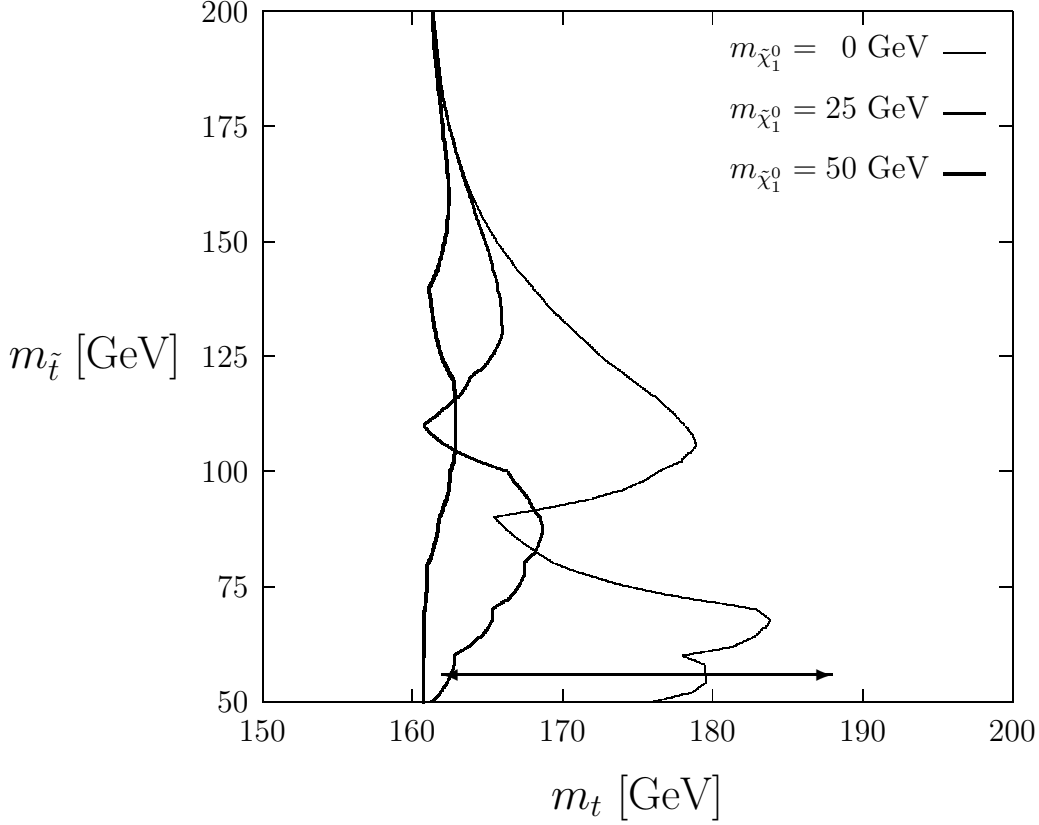


Fig. 4. Solutions of  $n(m_t, m_{\tilde{t}}) = 7 - \sqrt{7}$  (cf. Eq. (3)), for three different neutralino masses. The solutions of  $n(m_t, m_{\tilde{t}}) = 7 + \sqrt{7}$  are located much further to the left at too low top masses. The arrow indicates the  $1\sigma$  top mass range from the CDF and electro-weak measurements.

than about 30 GeV,<sup>1</sup> the stop squark mass is below 130 GeV and this mass is not within 10 GeV of the  $\tilde{\chi}_1^0 W b$  threshold, one obtains agreement with the mass measurements at the  $1\sigma$  level (down from  $1.6\sigma$ ). One might argue that if stops are produced along with tops the event reconstruction is bound to yield unreliable results. However, the number of stop events contributing is too small to seriously invalidate the kinematical mass determination of the top quark.

The reason why the stop signal is hardly included in the CDF sample is simple. If the stop is heavy (say  $m_{\tilde{t}} > 150$  GeV) its production cross section is too low. On the other hand, if the stop is light (say  $m_{\tilde{t}} < 150$  GeV) the two non-observed neutralinos carry off so much energy, that the remaining visible particles have barely enough energy left over to pass the strong overall 85 GeV transverse momentum cut imposed by CDF on the signal. This can be clearly seen in Figs 3 and 4, where in the neighbourhood of the  $\tilde{\chi}_1^0 W b$  thresholds the stop efficiencies drop to zero. Only almost massless neutralinos leave enough

<sup>1</sup> A massless neutralino cannot be completely excluded if  $\tan \beta < 2$ .

events to make a difference.

## 5 Conclusion

It has been suggested [3] that the excessive top quark cross section observed by the CDF collaboration can be explained by the production of light stop squarks, whose decays mimic the top signals. We have shown that this is unlikely to be the case. Although the signals look the same superficially and the cross sections can be similar, some of the cuts used by CDF to perform their analysis exclude many possible stop events from the observed sample in all but a small corner of the supersymmetric parameter space ( $m_{\tilde{\chi}_1^0 W b} < 30$  GeV,  $m_{\tilde{t}} < 130$  GeV and not within 10 GeV from the  $\tilde{\chi}_1^0 W b$  threshold). Note, though, that this conclusion only concerns the observability of stop squarks in the top sample; the possibility of observation in dedicated searches is not touched upon.

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